On the rotation rates and axis ratios of the smallest known near-Earth asteroids—the archetypes of the Asteroid Redirect Mission targets

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Abstract

NASA's Asteroid Redirect Mission (ARM) has been proposed with the aim to capture a small asteroid a few meters in size and redirect it into an orbit around the Moon. There it can be investigated at leisure by astronauts aboard an Orion or other spacecraft. The target for the mission has not yet been selected, and there are very few potential targets currently known. Though sufficiently small near-Earth asteroids (NEAs) are thought to be numerous, they are also difficult to detect and characterize with current observational facilities. Here we collect the most up-to-date information on near-Earth asteroids in this size range to outline the state of understanding of the properties of these small NEAs. Observational biases certainly mean that our sample is not an ideal representation of the true population of small NEAs. However our sample is representative of the eventual target list for the ARM mission, which will be compiled under very similar observational constraints unless dramatic changes are made to the way near-Earth asteroids are searched for and studied.

We collect here information on 88 near-Earth asteroids with diameters less than 60 meters and with high quality light curves. We find that the typical rotation period is 40 minutes. Relatively few axis ratios are available for such small asteroids, so we also considered the 92 smallest NEAs with known axis ratios. This sample includes asteroids with diameters up to 300 m. The mean and median axis ratios were 1.43 and 1.29.

Rotation rates much faster than the spin barrier are seen, reaching below 30 seconds, and implying that most of these bodies are monoliths. Non-principal axis rotation is uncommon. Axial ratios often reach values as high as two, though no undisputed results reach above three. We find little correlation of axis ratio with size. The most common spectral type in the sample of small NEAs is S-type ($> 90\%$), with only a handful of C and X types known.

Keywords: asteroids, composition; asteroids, rotation; Asteroid Redirect Mission (ARM); Near-Earth asteroids (NEAs)

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1. Introduction

In a detailed study of a hypothetical mission to retrieve a small asteroid and bring it to near-Earth space, the Keck Institute for Space Studies (KISS) report (Brophy et al., 2012)[1] concluded that "one of the most challenging aspects of the mission was the identification and characterization of target NEAs suitable for capture and return" (p.7). The report also outlines three key mission drivers, one of which is "the size and mass of the target body" (p. 28); the two others are the total delta-v required for capture and return, and the total flight time.

The design of the Asteroid Redirect Mission or a similar mission depends significantly on the properties of the target, namely its mass, size, density, internal cohesiveness, spin state, surface roughness, presence/absence of regolith and so forth. In the ideal case, mission planners will have complete information on the target's characteristics before launch. However, the near-Earth asteroids in the appropriate size range, which we will refer to as Very Small Asteroids or VSAs, are particularly difficult to characterize. They are faint and spend only a short time (typically days) within easy reach of Earth-based telescopes when they are first discovered, often not returning to the Earth's vicinity for several years.

Only relatively few of the already-known near-Earth asteroid population make suitable targets, as most known NEAs are simply too big. The discovery rate of suitable asteroids for the ARM was estimated in the KISS report (Table 2) to be five asteroids per year if a low-cost ground-based telescopic campaign was begun specifically to search for such asteroids; however, such a dedicated program is not yet in place. The total known sample of potential targets as of June 2014 is only nine[2] and what is known of their properties is scattered throughout the literature and internet. By collecting information on the smallest known NEAs, we hope to make the discussion of relevant design issues simpler.

The heliocentric orbit of the asteroid can be relatively easily determined, requiring only a handful of astrometric measurements from short imaging exposures, and the orbit provides enough information for the mission to be launched and to arrive at its destination successfully. Not that a high-precision orbit can necessarily be determined from the few-day apparition of a newly discovered small asteroid, but orbits are typically easier to measure than the asteroid's physical and internal properties and this may limit how accurately the density, spin state, taxonomy, etc. of the target is known before the mission proper is launched. Though there is always the option to study the target intensively when it makes a subsequent passage near the Earth, these opportunities may occur only at intervals of years, decades or even longer, and waiting for them could delay the mission significantly.

Furthermore, even careful study may not reveal all the properties of interest of a particular target. Hergenrother and Whiteley (2011) and Kwiatkowski et al. (2010b) examined the light curves of many small asteroids, and they point out that these are not always conclusive. Non-detections of asteroid brightness variations could indicate a non-rotating body, but could also be the result of asteroid shapes that are close to spherical, viewed pole-on and/or with rapid rotation periods that are not properly sampled by the exposure times used. Since smaller asteroids have a tendency to rotate rather quickly compared to large ones (Pravec and Harris, 2000), issues of this sort complicate the picture. Studies such as the present paper of the properties of the ARM target population as a

[1] Available at *http://kiss.caltech.edu/study/asteroid/asteroid_final_report.pdf*, retrieved 2014 Jul 24

[2] NASA Announces Latest Progress in Hunt for Asteroids, http://www.jpl.nasa.gov/news/news.php?release=2014-195, retrieved 2014 Nov 9

whole can shed light on the probable characteristics of individual targets for which some properties cannot be measured prior to launch.

Considering as well the long flight time for the ARM (six to ten years), it is conceivable that an incompletely characterized asteroid with a particularly favorable orbit (i.e. one that would result in a shorter travel time or a lower delta-v, and hence a lower cost for the mission) might be more enticing as a candidate than a better-studied small asteroid whose orbit is less favorable. As a result, a statistical study of the properties of small asteroids in general provides helpful insight as to the likely or worst-case properties of a potential target that is not yet fully characterized.

In the following sections, we collect the information available on VSAs in an attempt to paint a picture of a typical asteroid within the size range suitable to be an ARM target. This picture will include the most likely spin-state, shape, and composition of such an asteroid. In addition, we will also discuss the "worst-case" scenario for an ARM target in terms of extremes of rotation rate and the likelihood of a tumbler or non-principal axis (NPA) rotator.

2. Methods

The body of results on asteroids within the desired size range is small. A large portion of the information presented here was gathered from the Light Curve Database (LCDB, Warner et al., 2009). Additional information was collected from published asteroid surveys presented by Whiteley et al. (2002), Kwiatkowski et al. (2010a), Kwiatkowski et al. (2010b), Hergenrother and Whiteley (2011), Hergenrother et al. (2012), Polishook et al. (2012) and Statler et al. (2013).

In obtaining data from the LCDB and the other surveys, we selected two samples. One contained the smallest asteroids with known rotation periods, and one the smallest asteroids with known axis ratios, as unfortunately not all small asteroids have measurements of both of these quantities.

The first sample was selected on two criteria. Firstly, given the scarcity of data on asteroids with diameters of ten meters and under we chose a sample of asteroids with estimated diameters of 60 meters and under as a proxy. The choice of 60 meters as our upper-boundary is arbitrary, but it gave us a sizable amount of data without straying too far from the intended diameter. It also allows some consideration of the alternative ARM scenario nicknamed *Pick Up A Rock*, where instead of retrieving an asteroid whole (the *Get a Whole One* scenario), a boulder or other material would be recovered from the surface of a larger body. Secondly, for data that came directly from the LCDB, asteroids with a quality rating U lower than $2-$ were not included in the study (The LCDB quality rating runs from 1 (low) through 1+, 2-, 2, 2+, 3- to 3 (high)). This first sample we will refer to as the $D \leq 60$ m sample, and contains 88 objects. We note that the diameter measurement is an equivalent diameter computed from the absolute magnitude and an assumed albedo. Such measurements invariably contain some uncertainty but this is not quoted in the LCDB and we do not discuss it here. For more information on the methods by which these quantities are deduced the reader is directed to Warner et al. (2009).

It proves difficult to find derived axial ratios (or a/b ratios) in the literature, and most members of our first sample do not have reported axis ratios. So a second sample was selected to increase the number of axis ratios available. Since the LCDB doesn't quote the necessary data, these asteroids are selected from the papers referenced in paragraph 1 of this section. We had to increase the size limit of the second sample to ~ 300m in order to obtain a sizable sample of known axial ratios (92 asteroids in total). We call this second sample the a/b ratio sample.

We note that asteroid shape – specifically its a/b ratio, assuming a simplified triaxial ellipsoid shape where the axis lengths are $a \leq b \leq c$ – is not typically a parameter that is calculated in most

light curve studies. To overcome this, a formula presented by Kwiatkowski et al. (2010a) was used in order to determine the minimum a/b ratio from two parameters that are usually found in most surveys; the light curve amplitude A and the phase angle α (Eqn. 1). We calculate the minimum axis ratio here (that is, we assume equality in Eqn. 1) which thus is a lower limit.

$$\frac{a}{b} \geq 10^{0.4A(\alpha)/(1+0.03\alpha)} \tag{1}$$

Non-principal axis (NPA) rotators (or tumbling asteroids) are also taken into account here. NPA rotation is unstable rotation that occurs when an asteroid is not spinning around its principal axis of maximum inertia, a state which may be caused by an impact with a meteoroid or another asteroid. During NPA rotation, energy is slowly dissipated from the asteroid until the body returns to stable principal-axis rotation. Information on whether an asteroid was a suspected tumbler is often recorded in the LCDB or the various surveys, though it should be noted that these asteroids have not all been confirmed to be tumblers. Some of these asteroids have been deemed possible tumblers simply because of the irregularity of their light curves, and further study is necessary to confirm NPA rotation. For the purposes of this study, if an asteroid is either a confirmed or possible tumbler, it has been designated as a tumbler in our samples. It is noted in Warner et al. (2009) that there may be selection biases against small fast-rotating tumblers due to the additional data required to properly analyze a light curve with tumbling characteristics, therefore there is a possibility that our study underestimates the true fraction of tumblers in the general VSA population.

3. Results and Discussion

3.1. Rotation rate

Figure 1 is a plot of rotational period versus effective diameter for our $D \leq 60$ m sample. The typical fast rotational nature of small asteroids mentioned in such papers as Pravec and Harris (2000) is apparent here with only 11 out of the 88 asteroids in the sample having a period longer than one hour. During the preparation of this paper 2014 RC was discovered, with the fastest rotation period yet reported at 15.8 seconds. We include it in Figure 1 for reference though it has not been given a quality rating by the LCDB yet and is technically not included in our $D \leq 60$ m sample. Asteroid 2010 EX_{11} (a 45 m diameter S-type) has the slowest rotation period at 9.4 hrs. Overall, the mean period was found to be 0.67 hrs or 40 minutes.

The two proposed fundamental types of structure for asteroids are monolithic and "rubble pile". Monolithic asteroids are made up of a singular boulder, held together by its own tensile strength. On the other hand, "rubble pile" asteroids are made up from a collection of gravitationally bound boulders, dust and regolith. These cannot spin faster than what is commonly called the "spin barrier" (e.g., Hartmann and Larson, 1967; Burns, 1975; Harris, 1996; Pravec and Harris, 2000) at around 2.2 hrs or the asteroid will fly apart, though the shape of the asteroid will affect the precise location of this boundary. Our analysis here confirms that a large portion of the VSA population consists of fast-rotating asteroids supporting the suggestion of Harris (1996) that they are monolithic.

All but three of the asteroids in Figure 1 have rotation periods above 60 seconds, but we will make special note here of the few that spin faster. The 3 meter S-type asteroid 2010 WA has a period of 31 seconds. 2010 JL_{88} is a 13 meter diameter S-type which appears on the graph at 25 seconds. For both of these asteroids the quality rating of the light curve data collected is $U = 3$, which is the highest rating. We also note asteroid 2014 RC, which has a diameter of 12 to 22 m and

a rotation period of 15.8 seconds[3] though a full analysis of the observations has yet to be published to our knowledge.

In its analysis of the asteroid capture process, the KISS report considered the de-spin of a hypothetical asteroid with a period of 1 minute. Though this assumption is quite reasonable, it is worth noting that there are a number of faster spinning asteroids in the current observational sample.

We find that VSAs are likely to be rapidly rotating, and thus are perhaps more likely to be held together by some tensile strength, as opposed to a "rubble pile". Holsapple (2003) however notes that relatively small cohesive forces are needed to hold a rubble pile together, far less than those present in dry terrestrial soils. It is also worth noting new observations made of a potential ARM target 2011 MD, an S-type asteroid with a diameter of 7 meters and a period of 11.6 minutes according to the LCDB. New infrared scans from NASA's Spitzer Space Telescope (Mommert et al., 2014) indicate a surprisingly high porosity, suggesting that it may be made up of a collection of small boulders rather than being a singular body. With its period being much faster than the spin barrier of 2.2 hrs, this implies that not all fast rotators are monolithic.

From Figure 1 it can be seen from the small number of green triangles that the fraction of tumblers in the VSA population is relatively small. Only eight out of the 88 asteroids collected in the $D \leq 60$ m sample have been deemed either confirmed or possible tumblers in the LCDB. Four out of the 92 asteroids collected in the a/b ratio sample have been deemed either confirmed or possible tumblers in the LCDB or the respective surveys in which their observations were presented; none of these tumblers overlap with those of the former sample. It would appear that tumblers constitute only a very small part of the VSA population as a whole, but as Warner et al. (2009) point out, the ratio of NPA rotators to principal axis rotators may be greater than what is presented here due to an inherent selection bias against small tumblers. We also note that the ratio of tumbler to non-tumblers is likely to be a function of size, axis ratios, etc.

3.2. Axial ratio

A plot of axial ratio versus diameter is presented in Fig 2. The asteroid with the greatest axial ratio is 2007 TS_{24} (a 65 m diameter S-type) at 2.8. This result is derived directly in Kwiatkowski et al. (2010b), although not without some discussion that is worth noting. Kwiatkowski et al. (2010b) mention that the strange light curve could be due to the asteroid being an NPA rotator, and hence it is marked as such in the figures.

Another important result discussed in Kwiatkowski et al. (2010b) is with respect to other asteroids with large a/b ratios, specifically 1995 HM and 2000 EB_{14}. Asteroid 1995 HM (a 94 m diameter S-type) was originally analyzed in Steel et al. (1997) and its unusual light curve ascribed to a possible banana shape, but was then re-analyzed in Whiteley et al. (2002) where it was given an APR (amplitude-phase relation)-corrected axial ratio of 3.1, which would give it the highest axial ratio known for VSAs. Asteroid 2000 EB_{14} (a 51 m diameter S-type) was given an axial ratio of 2.9 in Whiteley et al. (2002), which would have placed it as the second highest axial ratio.

Kwiatkowski et al. (2010b), however, recomputed the results to be 2.6 and 2.4 for 1995 HM and 2000 EB_{14} respectively, leaving 2007 TS_{24} with the highest axial ratio, and 1995 HM with the second highest. Since, as discussed earlier, we used the method of a/b ratio calculation of Kwiatkowski et al. (2010a), we present their result in the above graphs for consistency. The precise

[3] http://neo.jpl.nasa.gov/news/news185.html, Retrieved 2014 Nov 9

value of these axial ratios remains to be determined, but the important point is that the current best upper limit for axial ratios with respect to VSAs is around 3, and it would be unusual to find a VSA with an axial ratio far above that. There are two caveats worth noting however. Firstly, large axis ratios result in large magnitude variations between telescopic exposures, and may cause high-amplitude bodies to be missed entirely, biasing our sample. Secondly, our method of determining axis ratios from the light curve from the formula of Kwiatkowski et al. (2010a) provides a lower limit. As a result, the axis ratios of small NEAs may be systematically larger than reported here.

Nakamura et al. (2011) concluded that small fast-rotating asteroids have a tendency to be more spherical than slowly rotating asteroids, but Kwiatkowski et al. (2010a) reported just the opposite. In Fig. 3 we find little correlation between the asteroid periods and their a/b ratios. Least squares fits to our samples do have slight upslopes however, 0.0198 hr^{-1} on the upper panel, and 0.0835 hr^{-1} on the lower panel, so our samples do have a nominal weak correlation. But these slopes are heavily leveraged by a few points at the right-most edge of the figures and should be interpreted with caution.

Histograms of the axial ratios of our two samples are given in Fig. 4. The a/b ratio sample has mean and median a/b ratios of 1.43 and 1.29. Our $D \leq 60$ m sample does not have enough information to compute axis ratios for all its members, but the mean and median a/b ratios of the 46 members of the a/b sample with diameters below 60 m are 1.46 and 1.36 respectively, consistent with the idea that size and axis ratio are not strongly correlated.

We note that there has been some discussion in the literature surrounding the determination of a/b ratios in Nakamura et al. (2011). Already in 2009, Warner et al. pointed out that low light curve amplitudes (which result in concomitantly smaller axis ratios) may simply be a result of finding the highest amplitude spectral peak in noisy data. In the LCDB itself, a significant portion of the data are in the quality range of $U \leq 1+$, meaning that they are of doubtful quality. A fuller explanation as to why some of this data were given such a low quality rating can be additionally found in Warner et al. (2009).

3.3. Taxonomic class and density

In addition to period and effective diameter, the LCDB also records the taxonomic class. Out of the 88 asteroids in our $D \leq 60$ m survey, 83 asteroids were of S-type (silicaceous “stony” objects), and out of the 92 asteroids in our a/b ratio sample (which does overlap partially with the previous sample), 89 were of S-type as well, making it the most common type in our specific asteroid population. The few other spectral types that were seen in the population were four asteroids in the C-group (carbonaceous objects, including one type B and one F), and three others being in the X-group (metallic objects). It is believed that 20% (Brophy et al., 2012) of the near-Earth asteroid population is C-type, but that they are harder to discover because of their lower albedos. Thus the C types are underrepresented in our sample, reflecting the reality that our observed sample is sharply limited by target brightness. We are not arguing here that the real NEA population is low in C types, but the set of potential targets for the ARM mission is likely to be.

Taxonomic class is linked to asteroid density, but for S-type asteroids we must take the size into consideration as well since, as Carry (2012) observes, the density of S-type asteroids appears to increase with mass. If we look at Fig. 9 in the paper just mentioned, S-type asteroids in the ARM size range would have an average bulk density of around 2.6 g cm^{-3}, though the density of S-type can be as low as 1.9 g cm^{-3} such as for Itokawa (Fujiwara et al., 2006). Given the predominance of S types among the small near-Earth asteroid population, it is reasonable to conclude that the density of most potential ARM targets will be in the same range though the density of a specifically

chosen C-type target would be lower, around 1 g cm^{-3} (Britt et al., 2002). The composition, mass and internal properties (rubble pile versus monolith) will all play a role here.

4. Conclusions

We have collected the available data on very small asteroids (VSAs) with the highest quality light curves. Unsurprisingly, a VSA will most likely be found to have a period under the "spin barrier" of 2.2 hrs; the average period from the $D \leq 60$ m sample analyzed here is 0.67 hrs or 40 minutes. The lower limit for the period of the current sample reaches down to 25 seconds (2010 JL_{88}, a 13 m diameter S-type) or even less (2014 RC, a 12-22 m Sq-type, with a period of 16 seconds) though shorter periods are possible.

With respect to structure, our results imply that a VSA will probably be a monolithic structure in which a singular boulder is held together by its own tensile strength, as opposed to a "rubble pile" in which many boulders are gravitationally bound together, although arguments from Holsapple (2003) and new evidence from Mommert et al. (2014) show that this may not necessarily be true.

We used the information on the light curves provided by various surveys to estimate the axial ratio. The VSAs in our samples have an average minimum a/b ratio of about 1.4, and the VSA with the greatest axial ratio was found to be 2007 TS_{24} at 2.8. Alternate analyses of some asteroid light curves have given slightly different values, but all VSAs observed to date are consistent with axial ratios less than three. The mission outlined by the KISS report discussed a capture bag capable of accommodating a 10x15 meter asteroid with a 2:1 axis ratio. Most ($> 90\%$) of our $D \leq 60$ m restricted sample have an a/b ratio less than 2, but a few exceed this value. We do note that our method of determining axial ratios from Kwiatkowski et al. (2010a) provides the minimum axial ratio consistent with the light curve amplitude, and so the values reported here are lower limits.

The composition of most potential targets is likely to be rich in silicates (S-type taxonomic class). The KISS study suggested that C-type asteroids would make more interesting targets because of their more diverse composition, which include water, carbon compounds, rock and metal. However, such asteroids are not common within the currently characterized small near-Earth asteroid population, though four C-group (including sub-types B and F) and three X-types appear in our sample. Though the real NEA population is not necessarily this low in C types, the list of potential ARM targets is likely to be poorer in carbonaceous bodies than might otherwise be expected.

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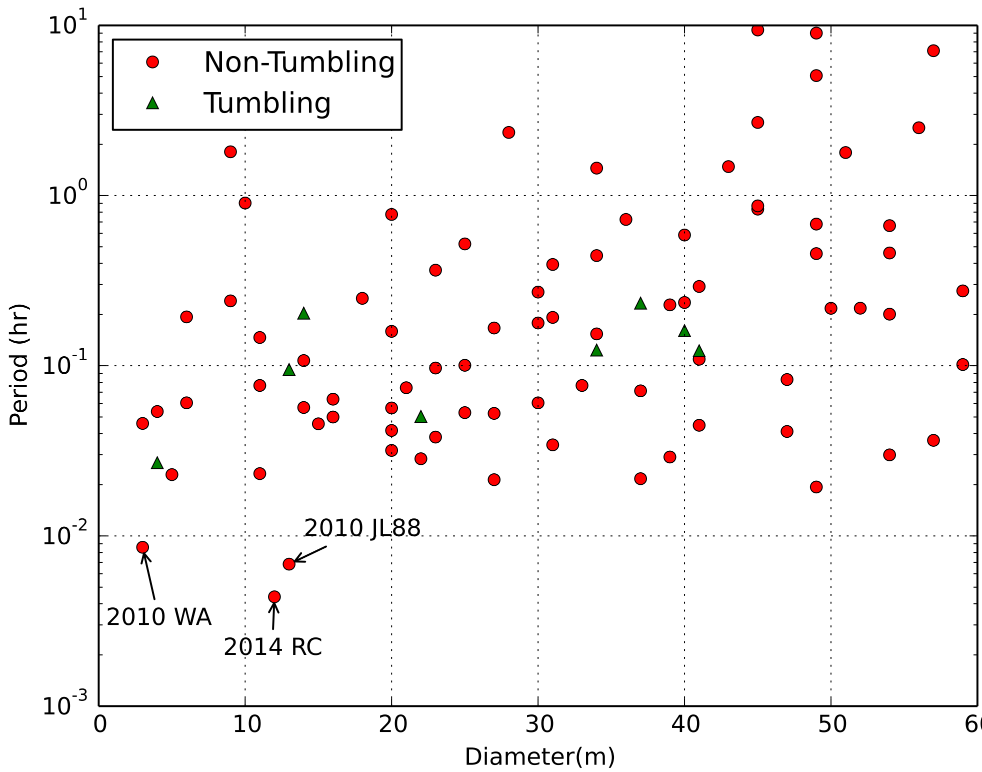

Figure 1: Period versus diameter for the $D \leq 60$ m sample. Green triangles indicate known or suspected non-principal axis rotators.. Asteroid 2014 RC is not part of this sample, but is added for reference.

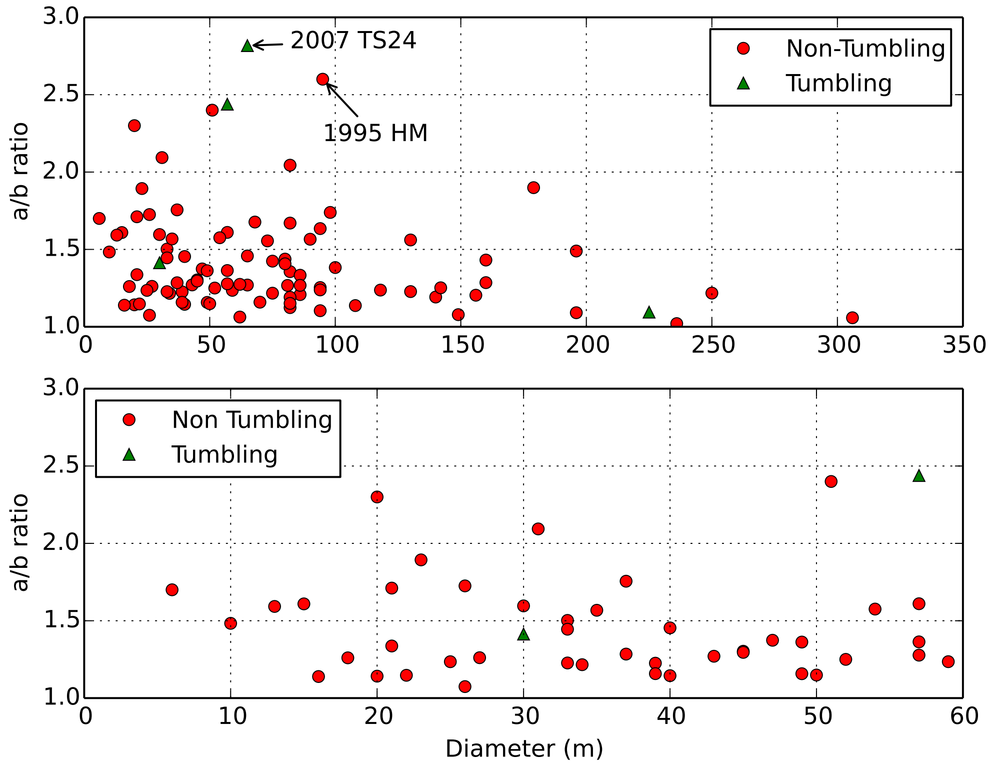

Figure 2: The a/b ratio versus diameter for the a/b ratio sample (top), and a portion of the a/b ratio sample with the restriction $D \leq 60$m (bottom).

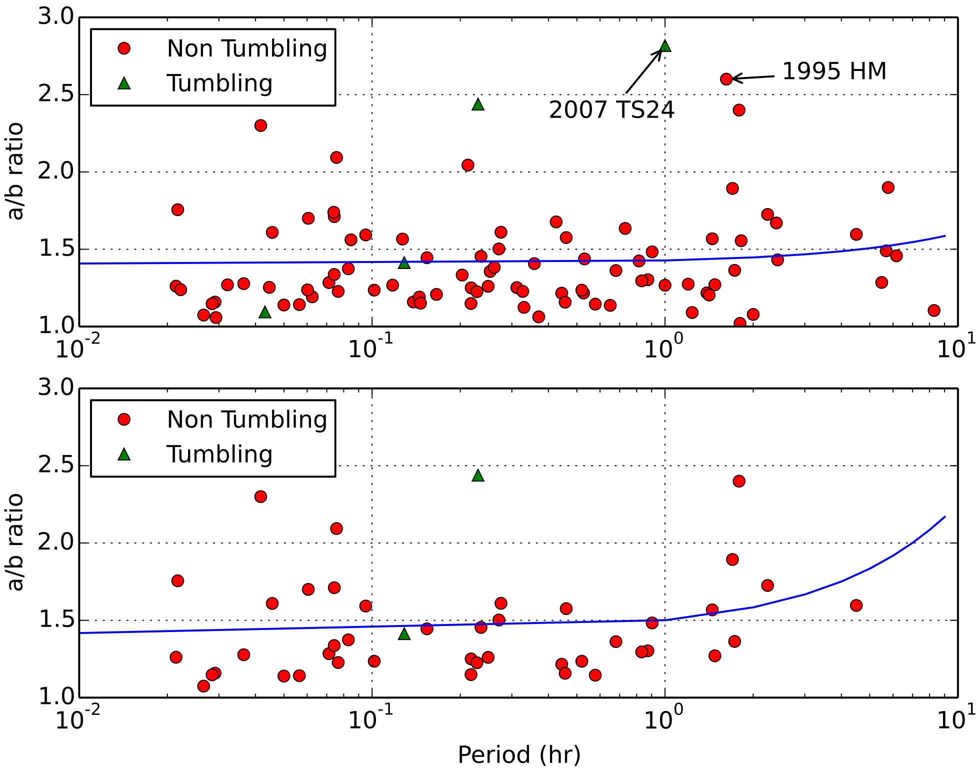

Figure 3: The a/b ratio versus rotation period for the full a/b ratio sample (top) and the $D \leq 60$ m restricted a/b ratio sample (bottom). A least-squares linear fit to the data is presented in blue. The best fit line appears curved here because of the logarithmic x-axis.

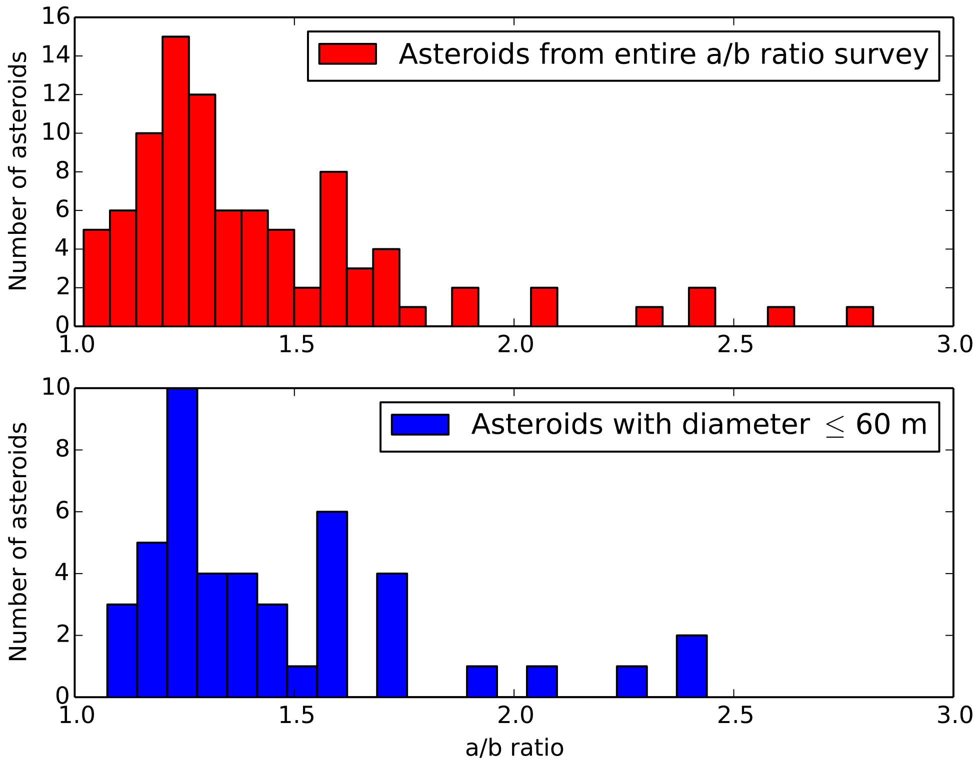

Figure 4: Histograms of the axial ratios of the full a/b ratio sample (top) and the $D \leq 60$ m restricted a/b ratio sample (bottom).